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RAY-MODELING FOR COMPUTER SIMULATION OF ULTRASONIC TESTING

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INTRODUCTION

One of the most important requirement in ultrasonic testing is understanding the wave propagation behavior.

Ultrasonic visualization methods have been applied for studying wave propagation and reflection[1-4]. Computer simulation analysis of wave propagation have also been conducted. A particles model[5], finite element models[6,7] and an iterative ray tracing model[8] were applied for such simulations. However, these are mostly concerned with the basic behavior of wave propagation and defect scattering.

For practical application, we propose a ray model of ultrasonic wave generation and propagation to simulate the ultrasonic testing, and applied this simulation technique to a welded joint model. The actual directivity of the generated wave was analyzed by the ultrasonic visualization system to include the sound pressure distribution in this model. In this ray model, a group of rays corresponded to the ultrasonic beam, and sound pressure was expressed as the density of rays. Reflection and mode-conversion were obtained according to Snell's law and variation of sound pressure at reflection was determined.

In this study, two kinds of welded joints models were used to investigate the validity of this simulation. Simulations of wave scattering and A-scan displays were agreed well with experimental results which were obtained using ultrasonic visualization system and actual ultrasonic testing.

OBSERVATION OF ULTRASONIC WAVE GENERATION

The ultrasonic shear wave visualized by the photoelastic ultrasonic visualized system[4] is shown in Fig. 1(a). The nominal frequency of this probe is 4 MHz and the nominal refraction angle is 60 degrees. The transducer dimension is 8 x 9 mm. Figure 1(b) shows the schematic diagram of generated wave. The shape of wave front was sectorial and the point source of the wave, or the central point of this sector, was located inside the probe. The directivity was almost constant during the propagation. The refraction angle of the probe was 65 degrees. This is due to the velocity difference between the steel and the glass used in this experiment. A directivity of sound pressure from this point is shown in Fig. 2 by analyzing visualized picture of Fig. 1. The directivity is symmetric with respect to 65 degrees direction.

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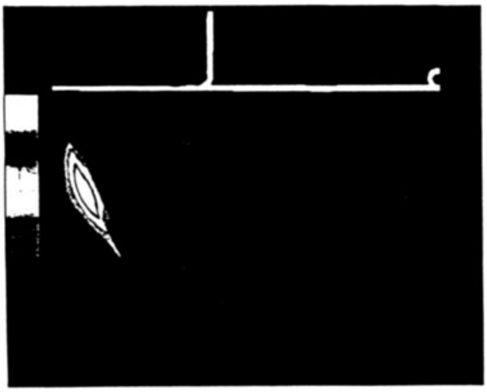
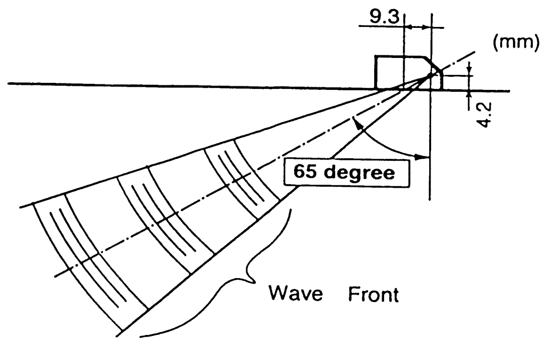


(a) Visualized picture



(b) Schematic diagram

Figure 1. Shear wave generation from an angle probe.

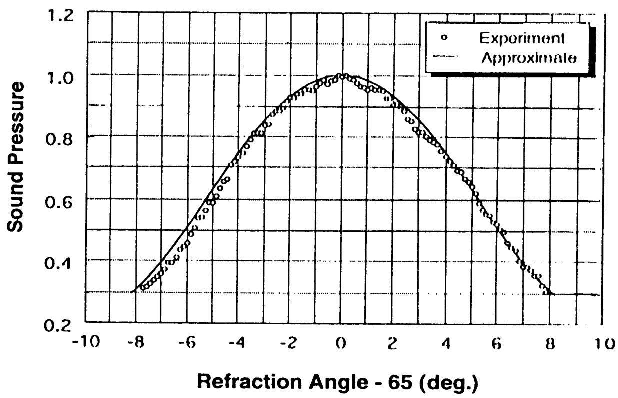


Figure 2. Directivity of generated wave.

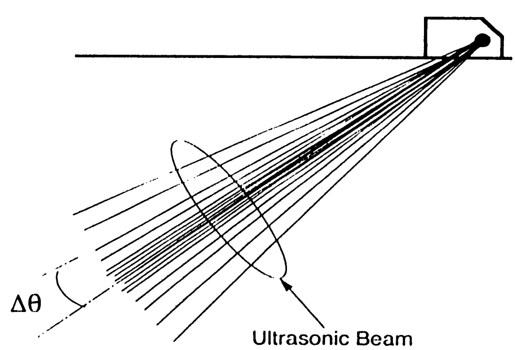


Figure 3. Schematic diagram of wave generation model.

The range of angles in which the sound pressure has decreased to -6 dB of the maximum pressure are 65±5.57 degrees. Sound pressure "P" relative to angle "ϕ" from 65 degrees could be expressed approximately as follows.

$$P = 1 - 0.017258\,\phi^2 - 0.00011\,\phi^4 \tag{1}$$

where P is normalized sound pressure

ϕ is radiation angle ± 65 degree

MODELING OF ULTRASONIC WAVE GENERATION

Since the ultrasonic wave generates from the point source, we made the simple model of the ultrasonic wave generation from the angle probe, showing schematically in Fig. 3. A group of rays corresponds to ultrasonic beam. They generate from the point source radially within 65 ± 5.57 degrees range. Each ray is expressed as follows in x-y plane.

$$y - y_0 = a_0\,(x - x_0) \tag{2}$$

where (x_0, y_0) is position of the point source

a_0 is tangent of ray direction

The density of rays corresponds to the sound pressure of the ultrasonic beam. In order to express decreasing sound pressure in this ray model, the radiation angle of a ray relative to the next ray is increased. The angle interval of each ray was determined from the actual sound pressure distribution of Equation (1) by the following equation.

$$\Delta\theta = \frac{\delta}{\dfrac{\int_{\theta-\delta/2}^{\theta+\delta/2} P(\theta)\,d\theta}{\int_{-b}^{b} P(\theta)\,d\theta} \times N} \tag{3}$$

where $P(\theta) = 1 - 0.017258\theta^2 - 0.00011\,\theta^4$

δ is Constant, N is the total numbers of rays.

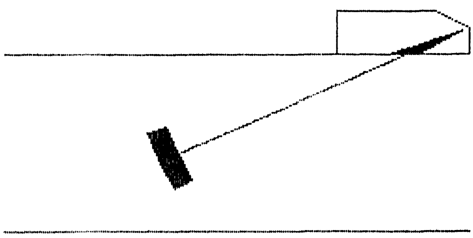
b = 5.57 degrees

Simulation result of ultrasonic wave generation using this ray modeling is shown in Figs 4. Figure 4(a) is the simulated wave front, showing the front of each ray which starts the point source and then propagates in the same time. The directivity of the simulated wave is shown in Fig. 4(b) with the experimental result obtained from visualized picture. This directivity was calculated using the number of the rays containing in every 1 degree range. This result agreed well with experimental results analyzed by visualization.

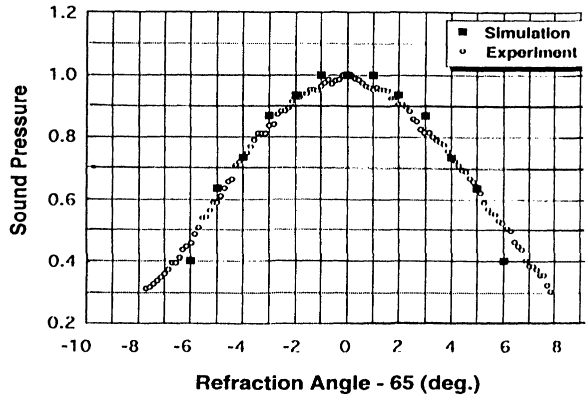
MODELING OF REFLECTION AND MODE-CONVERSION

We modeled the shape of a specimen using some equations to determine the surface data in simulation program. We find the reflection point of the ray by solving the equation of the ray (equation (2)) and the specimen shape.

Each ray branches at reflection by mode-conversion. Both the angles of reflection and



(a) Wave front



(b) Directivity

Figure 4. Simulation of wave generation.

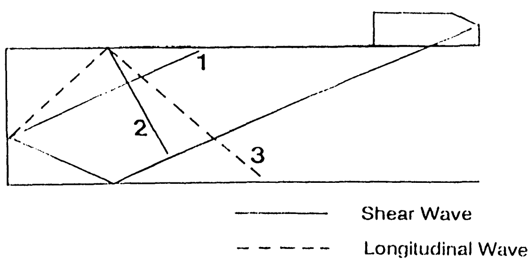
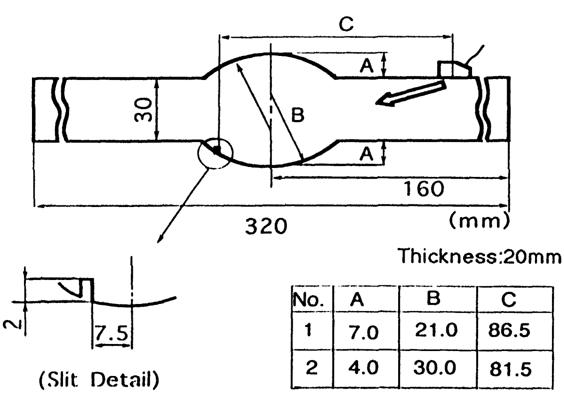


Figure 5. Simulation of wave reflection and mode-conversion.



No.	A	B	C
1	7.0	21.0	86.5
2	4.0	30.0	81.5

Figure 6. Dimensions of specimen (model butt welded joints).

mode-converted wave were obtained according to Snell's law. The example of reflection and mode-conversion of the rays are presented in Fig. 5. One ray starts from the point source and branches at reflection. These are the three rays which propagate during the same time. No. 1 ray shows that shear wave propagates and reflects twice without mode-conversion. No. 2 ray shows that shear wave is converted into longitudinal mode at the second reflection and re-converted into shear wave at the third reflection. At the first reflection, mode-conversion does not occur because of the large incident angle to the bottom surface. No. 3 ray shows that the converted longitudinal wave is reflected. Such reflection and mode-conversions were calculated for all rays in present simulation.

The variation of the sound pressure of ultrasonic wave by reflection or mode-conversion were calculated using reflection coefficient[9], where the sound pressure of the incident wave was taken as "1". For example, the sound pressure of No. 1 wave is determined as $1 x C_{1ss} x C_{2ss}$, where C_{1ss} and C_{2ss} are the reflection coefficient at the first and the second, respectively. The sound pressure of the No. 2 wave is $1 x C_{1ss} x C_{2sl} x C_{3ls}$, and that of the No. 3 wave is $1 x C_{1ss} x C_{2sl} x C_{3ll}$, where C_{2sl}, is the reflection coefficient of the mode-converted longitudinal wave at the second reflection, C_{3ls} is that of the mode-converted shear wave at the third reflection, and C_{3ll} is that of the longitudinal wave at the third reflection.

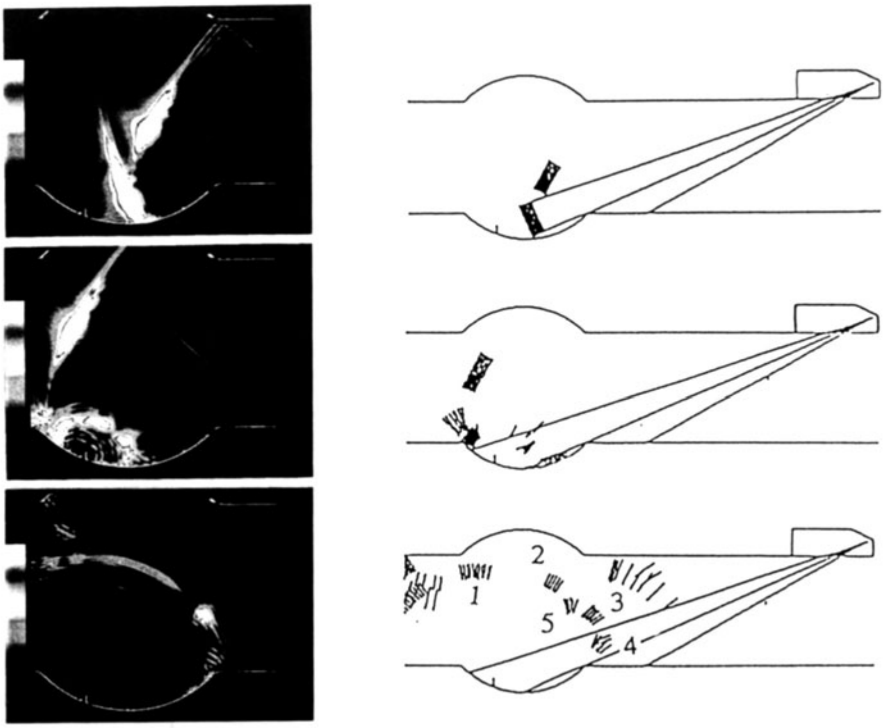
Every ray propagates with the data of the sound pressure, the direction, the propagating time, and wave mode. The propagating time can be calculated using wave propagation distances and wave velocity. The data of the sound pressure and propagating time of the ray was used for the echo simulation and the directivity simulation.

All rays which returned to the probe were taken as the echoes. We simulated an A-scan display of the ultrasonic testing using these received rays. An echo position in the A-scan display is calculated using the propagation time of each received ray. The echo amplitude is calculated using the summation of a received sound pressure of each ray and the received sensitivity of the probe. The received sound pressure is determined by the final sound pressure of the ray which received within the same time.The received sensitivity is calculated using the Equation (1) with the angle of the received ray.

RESULTS

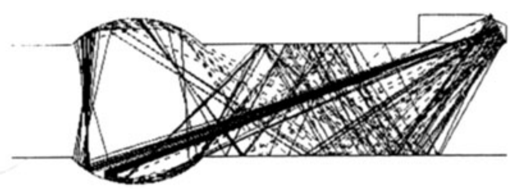
A glass specimens shown in Fig. 6 were used to investigate the validity of this simulation. They were the model of butt welded joints with round shaped weld reinforcement and an artificial defect. Specimen No. 1 and 2 have different shape of the weld reinforcement. They were made of Pyrex glass. The velocities of longitudinal wave and that of shear wave and density are 5490 m/s, 3420 m/s, and 2119kg/m^3, respectively. Probe position of specimen No. 1 is 81.5 mm far from the defect, and that of No. 2 is 86.5 mm, where maximum echo amplitude was observed in actual ultrasonic testing.

Actual ultrasonic wave propagation through the specimen No. 1 were visualized in Figs. 7 (a), showing the shear wave incident to the defect and its scattering at the defect. Figures 7(b) shows the simulation results of ultrasonic wave propagation through the specimen. The groups of rays are the wave fronts by showing the front part of the same time propagation from the source. The mode-converted longitudinal waves are marked "L". By comparison of Figs. 7(a) with 7(b), the simulations of wave propagation agreed well with experimental result which were actually visualized.

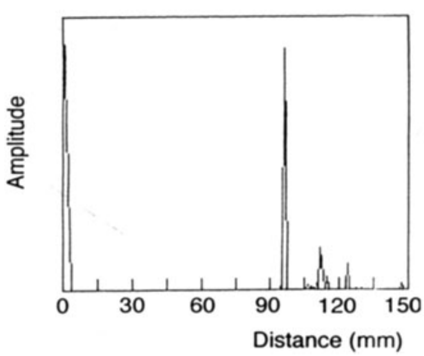


(a) Visualization (b) Simulation

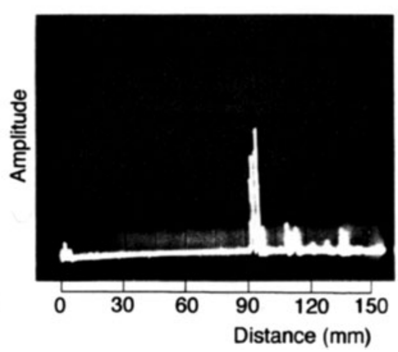
Figure 7. Wave scattering from defect.



(a) Various beam paths of echoes

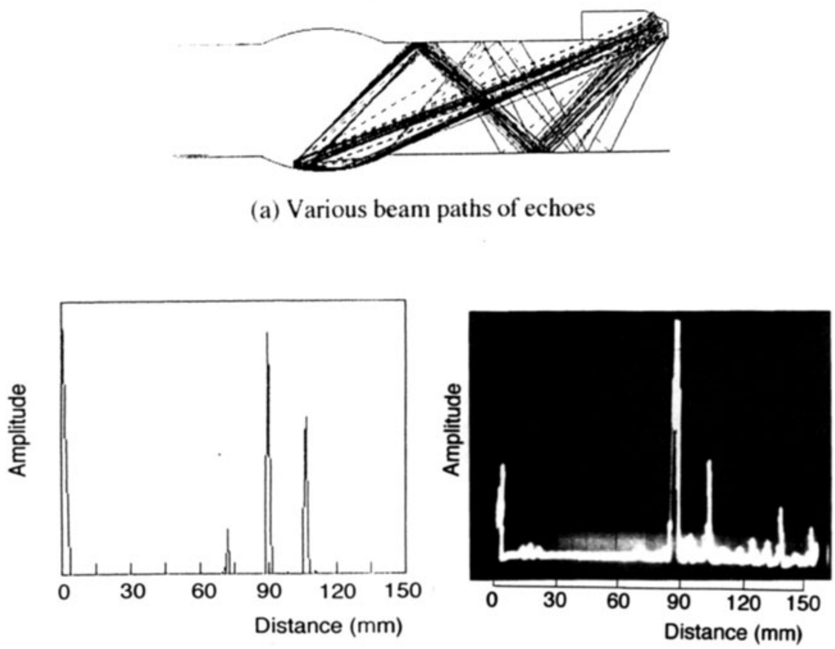


(b) Simulation of A-scan display



(c) Actual A-scan display

Figure 8. Ultrasonic testing of specimen No. 1.



(a) Various beam paths of echoes

(b) Simulation of A-scan display

(c) Actual A-scan display

Figure 9. Ultrasonic testing of specimen No. 2.

The results of the ultrasonic testing of the specimen No. 1 and 2 are shown in Figs. 8 and 9, respectively. Figure 8(a) and 9(a) are various paths of echoes in this simulation. The simulations of the A-scan display are shown in Fig. 8(b) and 9(b). Figure 8(c) and 9(c) show the actual A-scan display. By comparison with simulation A-scan displays and experimental results, the simulations are agreed with actual A-scan displays, respectively. This simulation can be predict both the A-scan display and the beam paths of any echoes in the display. The simulation indicated that the beam paths of echoes were quite different as the difference of reinforcement shape according to Fig. 8(a) and 9(a).

CONCLUSIONS

In this study, the ultrasonic wave generation and propagation were modeled to simulate ultrasonic testing, using the photoelastic ultrasonic visualization system. Ray-modeling is proposed for the modeling. In this ray model, sound pressure field expressed as the density of rays. Each ray branches at reflection or refraction by mode-conversion, and reflection or refraction angles were obtained according to Snell's law. Variation of sound pressure at reflection was determined using reflection coefficient. Simulations of wave propagation and A-scan display were agreed with actual visualization and ultrasonic testing results. This simulation is useful for understanding the wave propagation in the specimen and A-scan display in the ultrasonic flaw detector.

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